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13. ABSTRACT (Maximum 200 words) Our objective was to develop tools to visualize, measure, and thus understand the physical processes active in the upper ocean in three dimensions on scales of meters to one kilometer. Our approach was an integrated one, combining engineering, design, static and dynamic modeling, fabrication of arrays, and the deployment and use of these arrays. We designed, built, and used a two-dimensional array for sampling a horizontal section of the thermocline. This was deployed in the strong tidal flows over Stellwagen Bank in Massachusetts Bay and collected data to both analyze its performance as a observational platform and to investigate internal tides and solitons at this site. Two different surface compliant arrays were tested, one a linear array based on an oil spill containment boom and the second a two-diemnsional, floating mesh constructed of polypropylene rope. Byhanging sensor strings down from these arrays, two and three-diemsional sampling of the very near surface ocean can be carried out.				
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INNOVATIVE PLATFORMS FOR UPPER OCEAN RESEARCH

Robert A. Weller
Dept. of Physical Oceanography, MS#29
Woods Hole Oceanographic Institution
Woods Hole, MA 02543-1541
Phone: 508-289-2508, FAX: 508-457-2163, Email: rweller@whoi.edu

Co-PIs: S. Anderson and R. Trask
Physical Oceanography Department
Woods Hole Oceanographic Institution, Woods Hole, MA 02543
sanderson@whoi.edu, rtrask@whoi.edu
Co-PIs: W. Paul and M. Grosenbaugh
Applied Ocean Physics and Engineering Department
Woods Hole Oceanographic Institution, Woods Hole, MA 02543
wpaul@whoi.edu, mgrosenbaugh@whoi.edu

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LONG-TERM GOALS

We seek an improved understanding of the dynamics of the upper ocean and the physical processes that determine the vertical and horizontal structure of the mixed layer.

OBJECTIVES

Our ability to fully visualize, measure, and thus understand the physical processes active in the upper ocean in three dimensions on scales from meters to one kilometer is at present very limited. The objective of this project is the development of the technology to make measurements from three-dimensional arrays within the upper ocean. The long term technological objectives for this project are to develop the engineering tools to model, design, build, deploy, and retrieve reliable horizontal submerged arrays and surface compliant two and three-dimensional arrays. These arrays will provide unique access to the ocean and the ability to sample horizontal as well as vertical and temporal variability.

APPROACH

Our approach was an integrated one, combining engineering design, static and dynamic modeling and operational experience. We designed, modeled and deployed a moored, two-dimensional array which had instruments distributed both horizontally and vertically in the surface boundary layer. This array was assembled from a pair of subsurface moorings deployed in 100 meters of water with a horizontal element between the moorings capable of spanning 160 meters at a depth of 15 to 20 meters below the surface. Spaced along the horizontal member at 30 meter intervals were five instrumented vertical strings extending to a depth of 45 to 50 meters. Two 48-inch steel spheres were used as buoyancy elements on the subsurface mooring. Instruments measuring temperature, pressure, conductivity, current velocity, tilt, and acceleration were placed along the horizontal member and on the vertical strings. In addition, trials were conducted with surface following, compliant moorings based on oil booms and polypropylene nets that allowed horizontal arrays of instruments to be deployed from the surface down to 5 meters depth. Subsequently the lessons learned and methodology developed were transitioned to use in applications.

TASKS COMPLETED

In the first year, 1997, a numerical model of a subsurface horizontal mooring was developed to aid in the evaluation of horizontal mooring designs. The numerical simulation and study of the performance of the horizontal mooring was performed using a general purpose numerical code, developed at WHOI, for calculating statistics and dynamics of moored and towed oceanographic systems. The simulation is built around a mathematical model of cable dynamics that includes the effects geometric nonlinearities, material nonlinearities, material bending stiffness, and material torsion. This permits accurate three-dimensional modeling of systems in which the cable goes slack. The nonlinear, one-sided boundary condition at the seabed is modeled as an elastic foundation for systems with cable lying on the bottom. The numerical implementation includes an adaptive time stepping algorithm to speed the solution of problems with high nonlinearity.

Several field tests were conducted in 1997. The holding capability of three types of anchors was tested. A standard cast iron cylinder was tested along with a cast iron cylinder that had been modified with steel plates to dig into the bottom as well as a third type of pyramid-shaped cast iron anchor. Three different anchor types were tow tested with the anchoring rope pulling at 45 and at 30 degrees relative to the sandy floor of Vineyard Sound. The anchors respond with a typical slip-stick response to applied anchor line tension. The Dome and Mace anchors were found to require significantly heavier units to result in the same net holding power as the DorMor anchors

On August 19, 1997, the first horizontal array was deployed off Provincetown, Massachusetts, in 100 meters of water. An instrumented horizontal element, 100 meters long, was tensioned between two sub-surface moorings at 20 meters depth. The three current meters and five temperature/pressure recorders were deployed along the horizontal element. In addition to these instruments, a motion measuring package was deployed in one of the two sub-surface mooring spheres. A significant storm passed through the area two days after deployment, testing the holding power of the anchors and the integrity of the system under rough weather conditions. The array was successfully recovered on August 27, 1997. All instrumentation deployed along the horizontal element collected data for the entire deployment.

Experience gained from the first deployment led to the design of a two dimensional array (Figure 1) which had sensors distributed both horizontally and vertically. To evaluate the

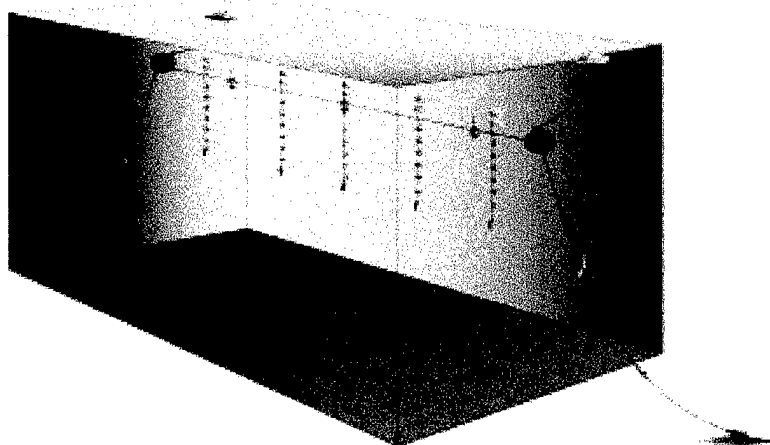


Figure 1. Schematic drawing of the horizontal array deployed off Provincetown in 1998.

unique capability of this two-dimensional array a joint engineering and scientific deployment was planned. The scientific focus was to explore the coherence at short horizontal and temporal scales of the internal waves on the continental shelf, specifically targeting internal solitons. Working in conjunction with the USGS a site was selected in Massachusetts Bay near Stellwagen basin in 85 meters of water.

The two dimensional mooring was deployed on August 6, 1998. In addition to having a single 160-meter long horizontal element tensioned at 20 meters depth between two subsurface moorings there was the addition of five 25-meter long vertical strings that were suspended from the horizontal member. The vertical strings had a horizontal separation of 30 meters and each had instruments at 20m, 25m, 30m, 35m, 40m, and 45m depth. The vertical string in the center of the array was instrumented with an acoustic current meter, five temperature and conductivity measuring instruments and one acceleration-sensing package. The other four vertical strings were each instrumented with six temperature recorders. The instruments at the bottom of the vertical strings also measured pressure. Two additional acoustic current meters were deployed along the horizontal member. Pressure sensors and motion monitoring packages were deployed at the ends of the horizontal member. The two dimensional array was successfully recovered on September 1, 1998 after 27 days on station.

In the third year, 1999, the focus was on exploring platforms that would allow for deployment of horizontal arrays just below the surface. The two elements were utilized for this where a 20 meter long oil boom (Figure 2) and a 20 by 8 meter polypropylene net (Figure 3) that was fabricated by the WHOI rigging shop. In July 1999, four - 24 inch

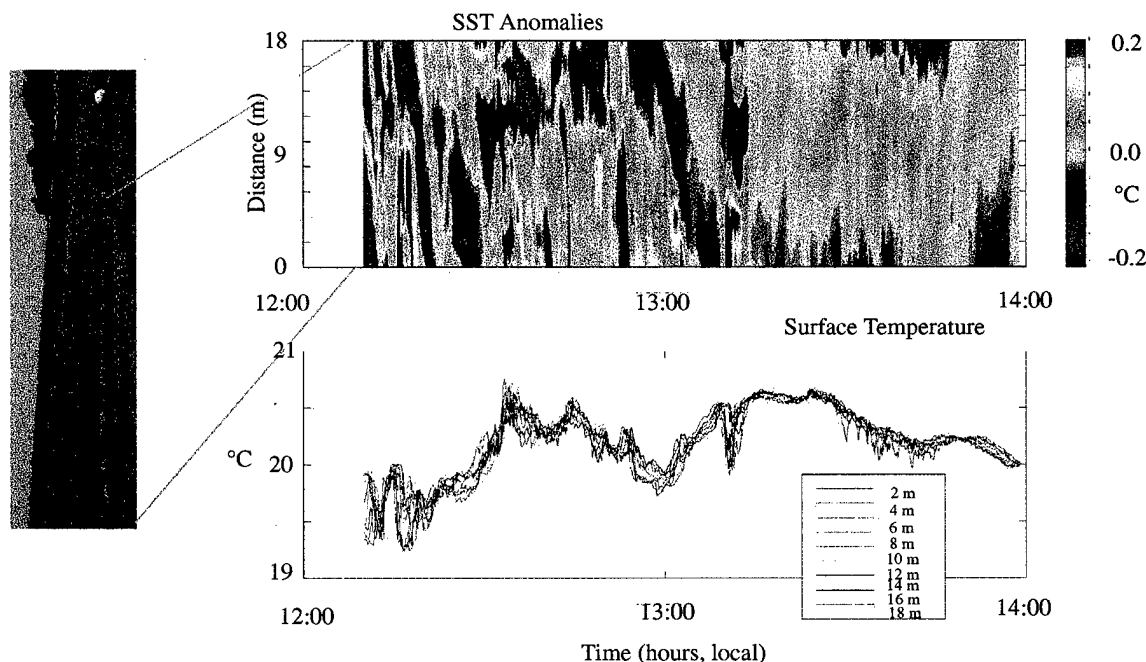


Figure 2. A 20 m linear array made from an oil control boom. Temperatures were recorded every 2 m along the boom just below the sea surface. Time series of absolute temperature and a contour plot of temperature anomaly show signals of several tenths $^{\circ}\text{C}$ in data collected at midday. In the anomaly field there is the suggestion of features that propagate with time. The addition of vertical sensor strings below the boom would return a 2-D slice of the surface boundary layer.

spheres were moored in a rectangle in Buzzards Bay at a water depth of 10 meters. These spheres were used as an anchor point for connecting the polypropylene net and oil boom.

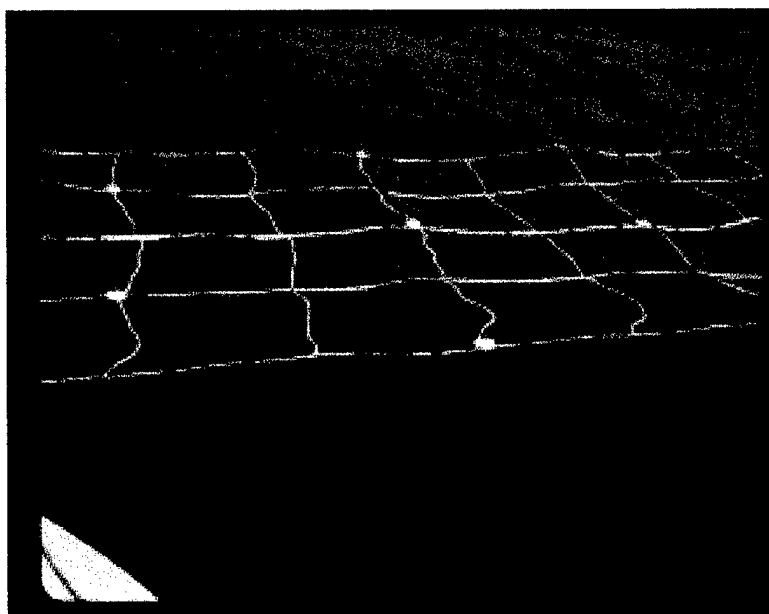


Figure 3. A 2-D mesh made from used polypropylene mooring line in order to test the feasibility of using such an approach to sample SST and the upper ocean. Suspending vertical sensor strings from the nodes of the mesh return a 3-D sampling of the surface boundary layer of the ocean.

These were successfully deployed across wind with temperature sensors and current meters located in the top 1 meter. The oil boom proved to provide more buoyancy and provide a more robust platform. In July 1999, the boom was moored in the center of Buzzards Bay for 24 hours with temperature instruments located at 0, 1, 2, 3 and 4 meters depth on five strings spaced 4 meters apart horizontally, in 16-meter deep water. In addition, a nearby mooring was instrumented with temperature sensors and current meters in a vertical array through the water column.

A no cost extension was requested and granted to carry remaining funds into 2000. These funds were used to finish analyses of the performance of the horizontal array deployed in 1997; this paper (Grosenbaugh et al., 2001) will soon be submitted. Scientific analysis of the data collected from the horizontal array was also carried out and a paper based on that is being prepared.

RESULTS

The technique developed to deploy the array proved quite successful. A mooring was deployed for one week with eight instruments, each with temperature and pressure sensors, spaced approximately 10 m apart over a horizontal span of 100m. The instruments were targeted to be 20m below the surface in 100m deep water. The range of instrument vertical displacements over a tidal cycle is confused by the surface displacement of the tide itself. However, the pressure records indicate that the instruments did not deviate from there

nominal position by more than 2m over a tidal cycle and daily mean depths changed by less than 0.6m over the 7 day deployment.

During the design and modeling phase of the moored horizontal array it was discovered that the anchoring system required careful review due to the expected loads, the nature in which the mooring system had to be tensioned to attain the desired performance and the size of the deployment vessel and its capabilities. A comparative anchor evaluation test was therefore conducted prior to the actual system deployment.

The anchor holding power as fraction of its weight was determined for the maximum holding force (= slip force) and the minimum anchor arresting force (stick force), measured in the anchor line. A new anchor type, a pyramid shaped cast-iron DorMor, showed consistently a stick force of about the submerged anchor weight, and a slip force between 1.58 and 2.2 times its weight. Mace anchors [deadweight steel with bottom skiffs] had a stick force of 66 to 79 percent of its submerged weight, and a slip force of about the anchor weight. A Dome anchor had a stick load of 59 percent and a slip load of 80 percent of its submerged weight. The Dome and Mace anchors would require significantly heavier units to result in the same net holding power as the DorMor anchors. The holding tensions did not change when the angle between anchor line and sea floor was decreased from 45 to 20 degrees. The proper sizing of anchors is most important in order to not lose the horizontal arrays in severe sea states with strong wave generated oscillating water motion near the sea floor. The local sea floor firmness needs to be tested under the effects of large surface waves although this effect should be somewhat limited at 100-m water depths (Traykovski et al 1997). A literature search has so far not produced reliable methods for the anchor selection.

The array specifications called for the array to be aligned so that it was perpendicular to the crests of the solitons that transit across Stellwagen Basin from Stellwagen Bank. The specification was for the mooring to lie along a 60°-240° line, true. This alignment was confirmed by visual inspection of the telemetry floats remaining on the surface and from the ship's compass to within approximately 10°. We conservatively conclude that the array was aligned within $\pm 10^\circ$ of the desired location. A more accurate survey could have been done if we had recorded the GPS location and alignment of each telemetry float individually prior to its removal from the array.

The design goal was to have the instruments be displaced by no more than ± 2 m from their design target depths. The design maximum current for this specification was 100 cm/s. The survival current was specified as 300 cm/s. Velocity data from the USGS ADCP located on the tripod positioned approximately 200m south of the array showed that the maximum observed currents were located in the depth range of the submerged array but did not exceed 100 cm/s. The sensor locations were determined using the pressure measurements from the Brancker, SBE and FSI instruments. The pressure record from the SBE tide gauge located on the anchor at 84m depth on the nearby subsurface mooring, monitored the local tidal elevation. This was subtracted from the sensor pressures as was an atmospheric bias determined from the time series just prior to the deployment of the instruments. This processing yielded a sensor position referenced to the bottom. There appears to be a slight tilt or sag in the array with the eastern end approximately 1m deeper than the western side. The bottoms of the strings did not vary by much more than 1m from their mean locations.

In conclusion, the submerged array was successfully deployed in the specified orientation and depth. There was an across array tilt of approximately 1m over 120m. The tidal currents did not lead to significant mooring motion, however, further modeling is required to understand the motion of the array in response to solitons. The observations of the

solitons are unique in providing a record of both horizontal and temporal variability (Figure 4) and these are being subjected to further scientific analyses.

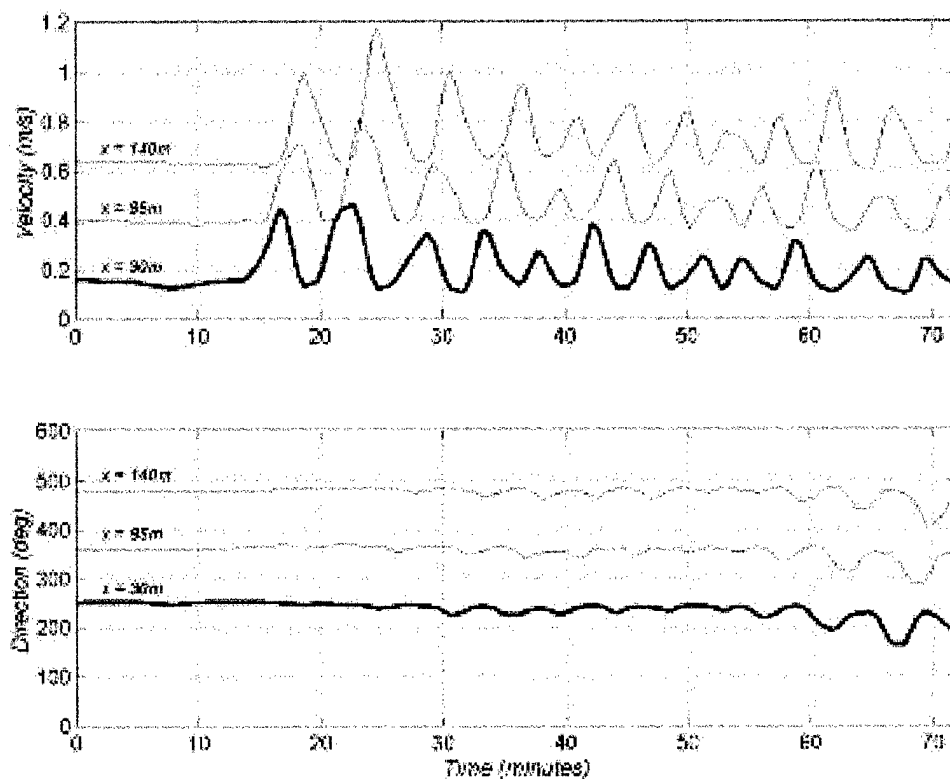


Figure 4. Speed and direction from 3 current meters spaced along the horizontal mooring at 25 m depth and at 30, 85, and 140 m from one end. Note the velocities associated with the passage of a train of waves.

While the horizontal array deployed off Provincetown did well at capturing variability in the thermocline, it was not a tool for use in sampling the very near surface region. The desire to develop methods to sample the near surface region lead to the further deployments of the linear and two-dimensional surface arrays shown in Figures 2 and 3. These deployments were successful. Deployment and recovery was manageable, and the platforms had the ability to carry useful payloads.

IMPACT FOR SCIENCE

The successful field deployment and recovery of an instrumented two dimensional array off Provincetown demonstrated the feasibility of using such moorings for scientific observations in the water column. In particular, it will be possible to investigate horizontal variability in the upper ocean on scales of meters to 100s of meters with high temporal resolution. Unlike towed thermistor chains, this new technology will allow for the complete measurement and resolution of the temporal and horizontal variability in the upper ocean. This program has documented the design, fabrication, and deployment methodology and recovered unique observations of variability over Stellwagen Bank.

The successful trial field deployments of the surface compliant arrays has provided the means to make observations very near the surface in two and three dimensions. This

methodology will be put to use by Weller in field work in the upcoming CBLAST-LOW (Coupled Boundary Layers and Air-Sea Transfers, Low Wind Program, ONR-funded to be in the water in 2001 and 2002) field work to be conducted south of Martha's Vineyard. The spatial as well as temporal variability of near-surface structure will be investigated under very light winds.

RELATIONS TO OTHER PROGRAMS

CBLAST-LOW

In this project Weller will examine horizontal variability in the upper ocean and in the surface forcing fields using several of the two and three-dimensional arrays developed under the innovative platforms project. This will provide information and understanding about horizontal variability in the upper ocean and in air-sea interaction.

1) Robert A. Weller, "The Coupled Boundary Layers, Air-Sea Transfer Experiment in Low to Moderate Winds (CBLAST-LOW)", ONR Grant (N00014-01-1-0029) [Lou Goodman], 7-00 through 12-04.

LOGLINE MOORING TO GROW MUSSELS OFFSHORE

Much of the learning about anchors and deployment methods was put to immediate use on testing horizontal moorings for mussel farming. A submerged longline was deployed in October 1998 at the WHOI Buoy Farm site, to serve as an experimental mussel aquaculture installation, called SCOMAS. This mooring did not use wire ropes; it was assembled from synthetic fiber ropes. Polyester anchor lines and a polyester covered polypropylene rope as long-line were selected. Chain sections formed the connections near anchors and corner buoys. A side view of the SCOMAS mooring is shown in Figure 5.

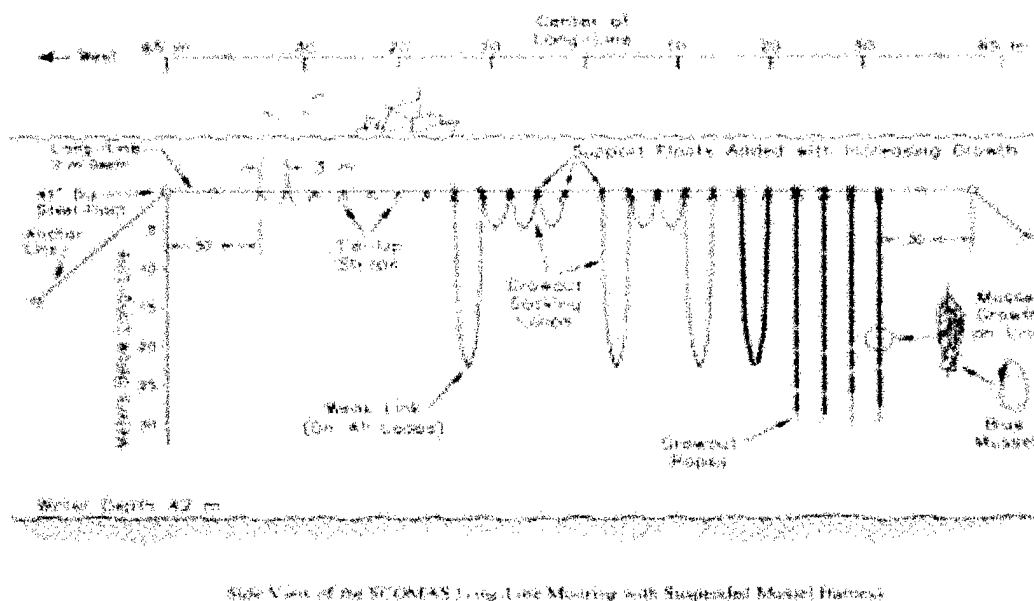


Figure 5. Schematic of mussel mooring.

The longline was anchored with two DorMor anchors, each weighing 4,400 lbs in air, details of the anchor and corner buoy moorings are shown in Figure 6. The system was retrieved after 19 months on station in June 2000, see Figure 7. A breakout force of 8,200 lbs was measured with a load cell. Or the DorMor anchor required a retrieval tension of about twice its weight in soft muddy sea floor, while it was sliding without slip stick action under half that tension just after deployment at the same site.

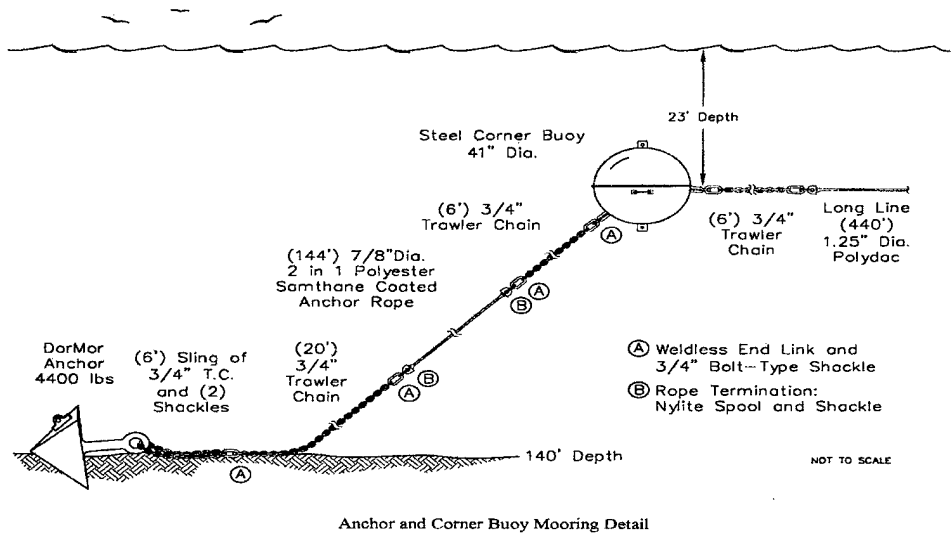


Figure 6: Anchor and Corner Buoy Mooring Detail

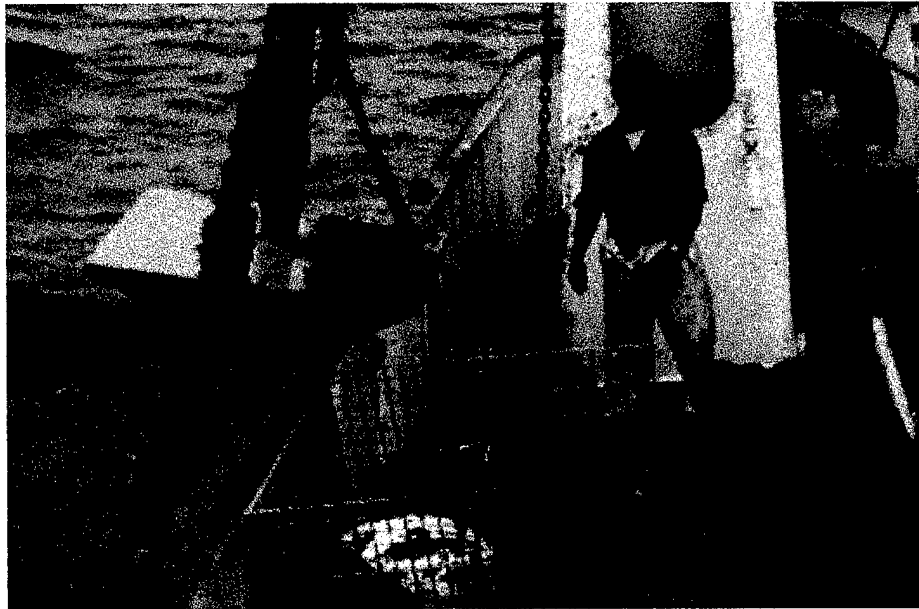


Figure 7: Retrieval of a 4,400 lbs heavy DorMor Anchor by the FV *Nobska*, after securing the long-line mooring at the WHOI Buoy Farm for 19 months.

Biofouling during longer deployments become a significant problem and potential benefit. After 8 months (October 98 through May 99) thick growth of grass-like Hydroids was found, see Figure 8.



Figure 8: Heavy growth of grass-like Hydroids on longline after 8 months at sea

However the Hydroids serve as habitat for blue mussels, which later out-compete the host plants and entirely covered the long-line and its suspended harness, see Figure 9.



Figure 9: Long-line anchor rope covered with blue mussel up to 18 inches thick after 19 months at sea

A close inspection of the long-line mooring after its retrieval and a thorough power wash showed very little or no wear on the entire installation. The center of the long-line, made up of two equally long sections is shown in Figure 10. One end was furnished with an eye-splice with thimble, and the other end was tied into the thimble with a bowline knot.



Figure 10: Bowline knot tie-in to thimbled rope eye in center of long-line after 19 months deployment at the WHOI Buoy Farm site.

The bowline knot could be readily unknotted and only showed an expected minor permanent deformation in the rope section forming the knot, see Figure 11 and 12. This is remarkable and indicates the fairly benign submerged environment in which the long-line mooring is stressed. A short section of the long-line showed more pronounced surface wear and repeated “stab wounds” from the grapnel hook interaction, needed to pick up and raise the long-line. This section will be replaced and is easily repairable with long splices. The mooring was exposed to high tensions during high state conditions including Hurricane Floyd in September 1999, and during the servicing of the mooring by larger support vessels.

A surface buoy mooring rope is expected to show considerably more signs of damage due to the continuous flexing and potential slack-snap conditions of the mooring near its buoy interface due to sea state effects on the surface buoy.



Figure 11: The bow-line knot loosened up. Some permanent configuration and local pressure spots, located in the center of the picture, indicate high tensions in service. But there is very little sign of surface abrasion, the rope looking almost new.

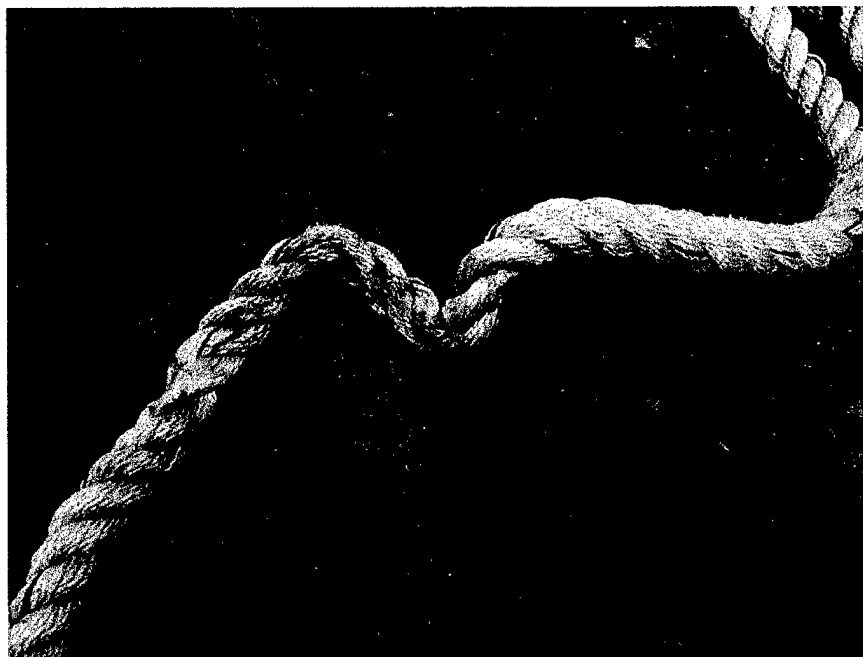


Figure 12: At the location of the former bow-line knot permanent deformation of the rope is found. Two permanent pressure points are seen in the center and the lower left of the image.

A permit application has been filed in November 2000 with the US Army Corps of Engineers and the National Marine Fisheries Service to deploy 30 long-line moorings at the WHOI Buoy Farm as a demonstration project for mussel growout in a small farm. This project is planned with a local fisherman who will procure and assemble the mooring systems, and harvest the mussels. WHOI will contribute with engineering design, monitoring of water quality, and measuring environmental and biological data. The installation is planned for a 24 month time period.

PARTICIPATION IN THE OPEN OCEAN AQUACULTURE PROJECT OF THE UNIVERSITY OF NEW HAMPSHIRE

Members of the WHOI Horizontal Mooring team became engaged in the Open Ocean Aquaculture program of the University of New Hampshire. Under this program two net cages and two mussel long-line moorings were installed in 1999 and serviced and improved in 2000 and continuing into 2001. The WHOI effort encompasses numerical modeling, review and recommendation of mooring hardware, assistance with deployment and retrieval operations, assembly and installation of load cells into the mooring grid of one of the net cages, and delivery of a wave monitoring buoy.

CONDUCTOR SURVIVAL IN LIGHTWEIGHT CABLES:

Helical arrangement of conductors around stretching strength members was applied on several projects and work well. The mechanics of such cables is explained in an upcoming paper.

1.) Dan Frye and Walter Paul: "Moored Array Technology", ONR Grant (N00014-94-1-0346) [Tom Swain], 1-94 through 12-97

2.) Walter Paul, Jim Irish, Sean Kery: "Modular Offshore Data Acquisition System"; Subcontract to a NASA Phase II STTR contract awarded to Jackson & Tull, Chartered Engineers, Washington DC, Feb. 1997 to Sept. 98.

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